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Sustainable sub-geothermal heat pump heating in Serbia

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ABSTRACT

Considering the necessity of improvement of Serbian energy production structure through higher participation of clean and renewable energy sources, the possibility of utilization of low enthalpy geothermal waters have been investigated. Energy potential of ground waters of modest temperature levels is usully neglected since it can not be used for direct heating purposes. Nevertheless, if the appropriate heat pump system is utilized, as described in the paper, the energy efficient and environmentally friendly heating could be achieved. From the environmental aspect particularly interesting would be the application of sub-geothermal heat pump in already existing high-temperature residential heating systems, as a complete substitution of old, low efficiency, highly polluting central heating of a building or a housing block. Besides environmental benefits of the proposed solution, obtained through shutting down the fossil fuel energy sources, paper investigates energetic efficiency of the model system, and discusses its economic justification. To achieve a full sustainability of the proposed heating system the environmental risks, especially deposition of utilized sub-geothermal water, need to be observed in detail.

Contents

1. Introduction

Heating of residential and office buildings consume almost one-third of Serbian energy production. The source structure of the utilized energy is highly adverse – less than 30% of heated objects, mainly in larger cities, are connected to the remote heating systems, while the rest use fossil fuels based individual or small scale central heating systems, with typically low energy efficiency and high atmospheric pollutant emission rates [1]. Moreover, it is estimated that almost one-third of households utilize electricity for space heating purposes.

Although the usage of energy efficient and environmentally sensitive energy sources is not widespread in Serbia in the moment, awareness of the necessity to evolve sustainable energy policy is established both in governing structures and among the population. The adoption of binding legal regulations in compliance with the EU directives [2], currently in progress, will result with implementation of stricter standards regarding environmental protection and more significant participation of renewable energy sources. Accordingly, the exploitation of geothermal energy sources will gain in importance [3].

The rground waters of modest temperature levels, between 10 and 30 °C are frequently found in the diverse regions of Serbia as well throughout Balkan Peninsula [4–6]. Such, *sub-geothermal* ground waters obviously have certain energy potential but, due to their low temperatures, cannot be used for direct heating purposes [7,8]. However, these energy sources can be efficiently utilized for heating if an appropriate heat pump system is applied.

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1.1. Sub-geothermal heat pump heating

There is a range of possibilities how a sub-geothermal water heat pump heating system can be designed and operated [8–13]. The system operates using *open* or *closed loop*. In an open loop system, water is pumped out of the well into a low temperature heat exchanger where a part of its thermal potential is used for refrigerant evaporation. Used water is returned into the ground or discharged otherwise. In a closed loop system, water remains underground and refrigerant, or another secondary heat transfer fluid, is circulated through the pipes sunk into the aquifer. Open loop systems have better overall efficiency, due to the lower thermal loses, yet they need more attention in terms of sustainable deployment of used water, as well as ground waters quality to avoid fouling and corrosion of the equipment (waters with high levels of salt, minerals, hydrogen sulfide, iron bacteria, etc., need to be pre-treated).

Depending on the temperature of ground water and temperature levels needed for ambient heating, one-stage or two-stage compression heat pump heating systems can be utilized. For the observed sub-geothermal sources (<30 °C), one-stage compression system can efficiently provide refrigerant condensation temperatures up to approximately 50 °C, that are sufficient for a variety of heating devices such as: panel radiator heating, floor heating, different fan coil systems, as well as advanced direct wall heating systems, etc. However, by further increase of one-stage heat pump outlet temperature, the compressor efficiency drops severely, annihilating in such manner the energy efficiency improvements. Hence, the one-stage heat pump systems are convenient only for the new buildings or the buildings subjected to radical reconstruction where the low temperature heating systems can be installed.

On the opposite, if the subject of heating system reconstruction is a building with existing hot water heating system installations (substations, pipes, pumps, radiator heating bodies in the rooms, etc.), as it is frequently the case in Serbia, a reasonable solution would be to keep and utilize most of the equipment and just replace primary heat source with an appropriate heat pump. Nevertheless, the temperature requirement for such a system cannot be reached in energy efficient manner by one-stage system, and therefore a two-stage heat pump system needs to be utilized.

The main evaluation parameter for all heat pump systems is *coefficient of performance* (*COP*) – the ratio between the produced thermal energy and the energy invested in heat pump operation (total compressors pumping power). Since a heat pump system usually consumes much less inlet power than its thermal energy production, legislative of European Union treat most heat pumps with high *COP* value (usually *COP* > 3) as renewable energy sources.

For Serbia, where about 750,000 households (26%) use hot water radiator heating (only in Belgrade: 300,000 households or 47%) [7], and the countries with similar predominant residential heating solutions and energetic policy heritage, such substitution of time-warn, low efficient and highly polluting central heating system

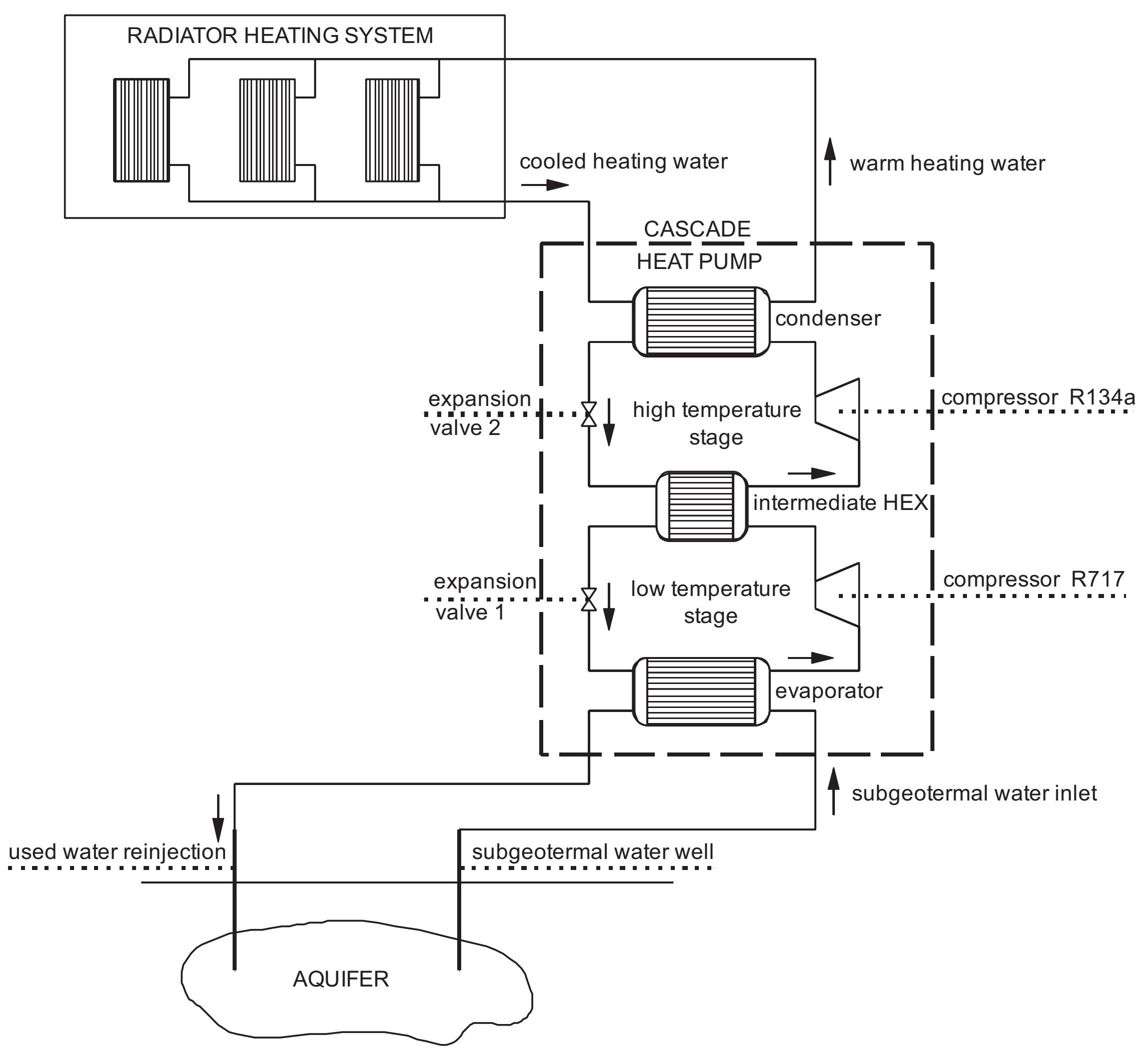

Fig. 1. Scheme of two-stage cascade heat pump and its coupling.

of a building or a housing block by a sub-geothermal heat pump, would be particularly significant. Additionally, if the targeted building has not been already connected to the remote heating system, the awarded energy effects are supplemented by substantial environmental effects arising from shutting down previously used fossil fuel energy sources such as crude oil or coal-fired power plants.

1.2. Cascade heat pump case study

Among two-stage heat pump systems capable to bridge a high temperature difference between the temperature of sub-geothermal water and the temperature requirement for hot-water heating, in an energy efficient and high-reliability manner, the two stage cascade heat pump has been adopted. To maximize performance, each stage of the heat pump uses different refrigerant, optimized for the temperature range. The principal scheme of the cascade heat pump and its coupling with an existing hot water radiator heating system is shown in Fig. 1.

The calculations of the heat pump heating system were performed for sub-geothermal water temperature ($t_{W,in}$) in the interval form 10 to 30 °C, covering the temperature range of most of sub-geothermal waters available in Serbia.

The temperature of condensation in high temperature stage ($t_{C,2}$) was set at 75 °C, in order to enable adequate operation of a radiator heating system in temperature regime 70/55 °C [13]. This temperature condition has proven itself as fully satisfying considering the facts that hot-water central heating systems in older buildings in Serbia, as the main target of the project, have been generally over-scaled; that the appearance of extremely low ambient temperatures that would impose need for higher heating water temperatures is very rear [5]; and that many of the buildings have been subjected to the improvements in thermal insulation during the last years. In addition, in order to study system efficiency and energy consumption during the whole heating season, further calculations with lower condensation temperature assumption, that could be used by milder atmospheric conditions, have been performed.

In particular, focus was set to the conditions at a location in municipality New-Belgrade chosen for the pilot sub-geothermal heat pump heating facility. The model object has area of about 2000 m^2 heated with hot-water radiator heating system. The location provides a sufficient amount of underground water, of average winter season temperature of $t_{W,in}$ = 16 °C, to cover maximal calculated heating requirement of around 200 kW. The foreseen depth of the intake well is 30 m.

Numerical simulations of the system, performed for several combinations of refrigerants, have shown that the best performing refrigerant match, in terms of overall *COP*, is R717 (ammonia) in low-temperature stage and R134a in high-temperature stage. Fig. 2 shows *COP* comparison of 3 best performing refrigerant pairs for underground water temperature of $t_{W,in}$ = 16 °C and temperature of condensation in high-temperature stage $t_{C,2}$ = 75 °C, by different values of temperature of condensation in low-temperature stage $t_{C,1}$. For the assumed conditions, and average temperature difference between the refrigerants in intermediate heat exchanger calculated at 8 °C, the curve of overall *COP* has its maximum for temperature of condensation in low-temperature stage of $t_{C,1}$ = 55 °C. For each set of temperature conditions and efficiencies of heat exchangers the value of maximal *COP* would appear by different value of $t_{C,1}$.

Temperature of sub-geothermal water has a considerable influence on the performance of the heat pump heating system. Fig. 3 shows how maximal *COP* of the heating system increases with rise of sub-geothermal water temperature. Therefore the system installation in urban areas, where *hot island effect* has been commonly recorded [7], is very favourable for its efficiency.

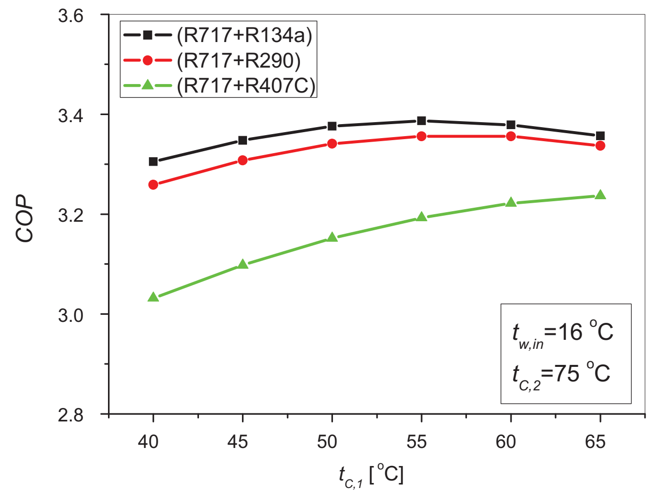

Fig. 2. COP dependence on low-temperature stage condensation temperature by different refrigerant combinations.

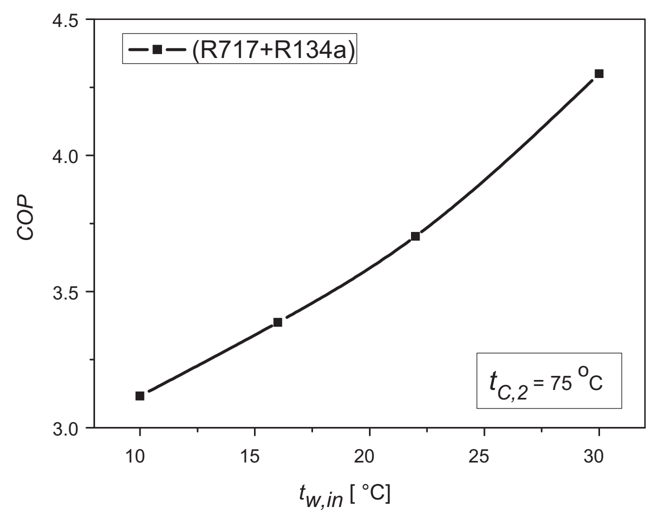

Fig. 3. Maximal COP dependence on sub-geothermal water temperature.

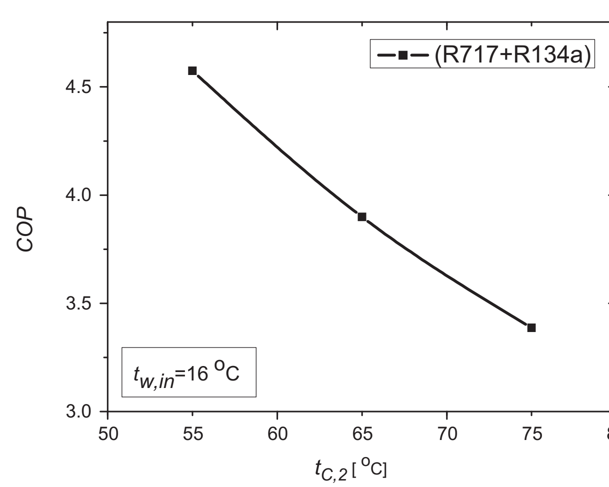

Fig. 4. Maximal COP dependence on high-temperature stage condensation temperature.

Since the local ambient conditions are mostly milder, the maximal thermal load will be rarely required and the system will dominantly operate in lower heating water temperature regime. Hence, the required condensation temperature $t_{C,2}$ will decrease and the system will commonly operate with higher *COP* values, as shown in Fig. 4. For example, the model system provides seasonal *COP* value of 3.4 for the harshest project temperature requirement ($t_{C,2} = 75\,^{\circ}\mathrm{C}$). In case of higher ambient temperatures system will be automatically set to work with lower condensation temperatures causing an increase of *COP*. Therefore, the average *COP* of the proposed system for the whole heating season, with daily temperature distribution defined on the basis of ambient temperature recordings in Belgrade during last 20 years [5], is expected to exceed 3.9!

The proposed heat pump system does not require any complicated underground heat exchangers, since water is pumped out of the well into a standard heat exchanger unit. Both, low and high temperature stage heat exchangers are water coupled and have substantially higher heat transfer rates than air-source or ground-source heat exchangers, enabling that way reductions in size, weight and price of the components. The intermediate heat exchanger, used for heat transfer from condensing refrigerant of low-temperature stage (ammonia) to evaporating refrigerant of high-temperature stage (R134a), must be designed and controlled-in-operation with full consideration, since its efficiency and reliability are valuable for the final performance of the heat pump system.

It should be emphasized that the proposed two stage sub-geothermal water heat pump can be installed directly into the existing central heating substations in relatively simple way and without any further interventions on the building, heating bodies or hot water distribution system.

1.3. Economic aspects

Economic analysis of the proposed cascade sub-geothermal heat pump heating system has been accomplished for the assumed intake well depth of 30 m, sub-geothermal water temperature 16 °C and capacity of 218 MWh/year, sufficient for radiator heating of 2000 m^2 space. Heat pump exploitation period is estimated to 15 years. The economic justification of the system is based on the projected economic flow that includes investment and annual exploitation costs, excluding depreciation and tax on the one hand, and revenues from heat energy sale, on the other [14]. Present value of the difference between revenues and costs is positive and shows economic justification of the investment. Positive economic net present value indicates that the observed heating system is also justified from the aspect of total economy. Economic internal rate of return is higher than the average productivity rate in the energy sector, hence the proposed sub-geothermal heat pump heating system is economically acceptable from the aspect of this criterion as well. Calculations show that the pay-back period of the investment is approximately 7 years, which is satisfactory for energy sector projects.

2. Environmental benefits and risks

The utilization of sub-geothermal heat pump technology promotes conservation of non-renewable energy sources and reduces dependence on energy import. The heat pump heating is more efficient than all heating systems based on direct combustion of fossil fuels: recent studies [9,15,16] have confirmed the CO_2 emission reductions of up to 80% by implementation of ground source heat pump heating in residential, commercial and institutional buildings. Furthermore, heat pumps with underground water as the heat source are more energy efficient than air source heat pumps, due to the lesser oscillations in heat source temperature over the year and typically larger temperature difference in exterior heat exchanger, as well as superior heat transfer rates in case of water instead of air as exterior media. The heat transfer behaviour is also an advantage of ground water heat pumps over various types of ground source heat pumps with exterior heat exchangers in shape of horizontal or vertical soil pipes or sondes [11,17].

The heat effect delivered by the observed sub-geothermal heat pump heating system is typically 3.2–4.5 times the electrical power input. In other words, compared to the electrical heating of the same end effect, overall power plant emissions are decreased by 3.2–4.5 times. The environmental benefits would be further propelled if compressors of the heat pump are power supplied by electricity produced from renewable sources, or natural gas driven.

The refrigerants selected for the heat pump system are R717 (ammonia) and R134. In regard to the parameters of environmental influence, both the refrigerants are superior to the customarily used Freon refrigerants [18–20]. Since the open system is proposed, the potential refrigerant, oil, and other substances leakages are localized in the central heating substations, minimizing the danger of ground water or soil pollution.

On the side of environmental risks it should be stressed that the open loop systems may contribute to aquifer depletion and subsidence of soil, if over-exploited or improperly utilized. Hence the environmental, hydrological, geological, as well as the technical aspects, need to be considered simultaneously in order to enable sustainable development of the targeted sub-geothermal aquifer system [15,21,22]. The proposed heat pump system should use a reinjection well to return the exploited water back into the aquifer. In practice, used water is sometimes released into local water courses or even directly into sewage, though this routine is prohibited in EU and many countries due to the risks of aquifers or water courses pollution [23,24]. In case of rural areas with adequate soil structure and aquifer depth and level, together with harmless chemical and thermo-physical properties of the released water, the specialized flood-ditches and ponds might be utilized to help returning water to the ground, but this approach imposes severe capacity constrains and potential environmental risks. With the reinjection the risks of aquifer deterioration is minimized, as well as the environmental concerns related to release of used water of different chemical composition and temperature in open water courses. After passing through the heat pump water could be directed into the same underground reservoir from which it has been pumped out. That could be achieved by direct insertion of used water into the aquifer, or by reinjection in the adjacent overlying strata in the way that the utilized, cooled, water reaches the reservoir with a certain delay.

Regarding the long term temperature stability of sub-geothermal waters, it would be favourable if the heat pump system is also used for cooling purposes during the summer season. By doing so the influence of used water, pumped back into the underground reservoir with lowered temperature during the heating season, would be partially neutralized, at annual level, by the water used for cooling during the summer months, reinjected with an increased temperature. Detailed information about the water reservoir and accurate modelling of heat extraction by the planned production rates [25], combined with efficient managenant in order to avoid over-exploitation (especially if more users exploit the same resource), would enable the hydro-geothermal system to reach a balance that can be maintained for a long time without notable heating performance deterioration [26].

3. Conclusions

As in European Union, where heat pump technology is anticipated to make about 30% of the aim for renewable energy in year

2020, in Serbia it should be a substantial fraction of the installed renewable energy sources during the next decade. Considering the large reserves of ground waters with energy potential sufficient for heat pump operation in Serbia, it has been concluded that the adequate sub-geothermal heat pump systems can contribute significantly to the fulfilment of the renewable energy targets.

The observed two stage, cascade, hydro-geothermal heat pump is foreseen as minimal pollution replacement for fossil fuel powered hot-water-heating systems. The system has shown a high-grade energy efficiency features by the observed boundary conditions. The positive environmental effects are maximized in case of complete substitution of old, low efficiency, highly polluting central heating of a building or a housing block, and exclusion of local fossil fuel energy sources. The installation in urban surroundings is simple, without major space requirements and building interventions. Optimized heat pump design, selection of refrigerants and operational control, joined with efficient aquifer development and management, insure energetic, economic and environmental sustainability of the proposed heating system.

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